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Juni 2014

Denne rapport er en del af den samlede rapport ”DTU’s undersøgelser af lav adhæsion / glatte skinner”, Journalnr. 12/07987

DTU Management Engineering
Institut for Systemer, Produktion og Ledelse

Management of low adhesion on railway tracks in European countries

Rapport 12/07987
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Dansk resumé

DTU's gennemgang af en række nordeuropæiske landes erfaringer med den praktiske håndtering af lav adhæsion / glatte skinner viser, at der findes en række håndteringsstrategier og dertil hørende tiltag og foranstaltninger på forskellige organisatoriske niveauer og områder: 1) Detektering og prædiktion; 2) Tekniske løsninger ved toget; 3) Forebyggende foranstaltninger langs banestrækninger; 4) Foranstaltninger rettet mod lokoførere og operatører. Den optimale sammensætning af tiltag er afhængig af dels den nationale togdrift (frekvens, køreplaner, m.v.) og dels af landenes jernbaneinfrastruktur.

Fælles for alle undersøgte landes vedkommende er, at ansvaret for håndtering af glatte skinner er fordelt på flere parter (operatører, infrastrukturejere, m.v.). For at opnå en optimal effekt af de forskellige tiltag er det afgørende, at de ansvarlige organisationer afstemmer redskaber og deres anvendelse med hinanden med henblik på at undgå, at optimering af isolerede og ukoordinerede indsatser fører til et suboptimalt samlet resultat. De internationale erfaringer tyder endvidere på, at hoveddrivkraften for de forskellige landes indsats mod glatte skinner primært er driftsrelateret, nemlig dels sikring af køreplan-regularitet, dels reduktion af slitage på hjul og skinner. Først i anden række motiveres tiltagene af hensynet til sikkerhed.

Danske tiltag

I Danmark er håndteringen af glatte skinner allerede i en årrække blevet betragtet som et fælles anliggende mellem infrastrukturforvalteren, Banedanmark (BDK) og alle jernbanevirksomheder, der kører på BDKs skinnenet. Der sker en koordinering mellem disse organisationer, primært med henblik på at sikre rettidighed i jernbanetrafikken og med fokus på løvfaldssæsonen (det vil sige fra 1/10 til 31/11).

Af BDKs notat af 23. oktober 2013 fremgår hvilke praktiske tiltag der aktuelt tages i brug:

- Vegetationskontrol langs sporene for at begrænse løv på skinner (BDK)
- Kørsel for at forhindre og opløse rustdannelser på skinnerne (BDK)
- Spuling af skinner for at rense skinnerne for eventuelle belægninger (BDK)
- Disponeringsplaner for afvikling af togtrafikken i løvfaldsperioden (BDK + jernbanevirksomheder)
- Instruktion af lokomotivførerne i kørsel under særlige forhold (jernbanevirksomheder)
- Vedligeholdelse af materiellets motorer og hjul (jernbanevirksomheder)
- Varslingssystem via togradio, som videregiver lokomotivførernes observationer til kollegaerne
- Systematisk opsamling af data om tog og evaluering af disse med henblik på en løbende optimering af forholdsregler og håndtering
- Systematisk registrering og analyse af data for signalforbikørsler siden 2006

Indsatsen er koncentreret på løvfaldsperioden og håndteres fra det fælles driftscenter for afvikling af togtrafikken på BDKs skinnenet (Driftcenter Danmark), som samler og analyserer data og koordinerer indsatsen.

Kgs, Lyngby, juni 2014
Jacob Thommesen, Nijs Jan Duijm, Henning Boje Andersen

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Adhesion management in European countries

1 Introduction

This report presents approaches of selected European countries to the management of low adhesion problems. It spans approaches addressing different levels of the problem, including preventive measures focusing on the tasks aimed at removing or reducing low adhesion, mitigative technical measures aimed at improving wheel performance in low adhesion conditions, as well as mitigative measures for driving and operating trains under these conditions. The report thus spans measures that are often managed by different organisations, mainly infrastructure managers and train operators.

The report focuses on management of low adhesion and will not go into detail with the characteristics and generation of the low adhesion layer but will touch on this only to the extent that this determines or is directly linked with the specific low adhesion measures taken. Neither will the report go into detail with purely technical aspects of e.g. braking and WSP systems, but focus on the implied requirements for organisations and drivers.

The report is largely based on literature describing measures taken by existing railway organisations, comprising, besides a few journal article, largely reports by railway organisations and authorities, supplemented by presentations from an International Workshop held at DTU on 16 April 2013 at which experts presented updated knowledge about measures in the UK, Germany, the Netherlands and Sweden

The background for this report was a DTU project originally focusing on a SPAD[1] incident in 2011 in Denmark and the braking ability of a specific type of train (Havarikommissionen 2012), but since expanded to encompass general problems with low adhesion (Nielsen et al. 2012). This report thus addresses problems that are already well-known to Danish railway organisations, but it gathers and analyses results and experiences from neighboring European countries that have similar climate, vegetation and rail infrastructures. This report provides information that is based on up-to-date research and experiments in countries, where this topic has been subject to systematic investigations and empirical research.

1.1 Low adhesion factors

In the following we shall be addressing primarily problems that arise in “very low” adhesion conditions but which also may arise with “low” adhesion. We shall use the term “very low adhesion” to denote an adhesion level below 0.05, sometimes also referred to as “exceptionally low” (AWG 2009). While wheel/rail adhesion is much lower than the adhesion of 0.9 characteristic of road traffic (Rijnaard 2013b), trains normally require 0.1 for braking, and 0.15 or higher for acceleration (AWG 2009).

Very low adhesion is caused by a third layer between rail and wheel. This layer is created by a contaminant or some contaminants which often in combination with light humidity are causing low adhesion. While wet

[1] Signal Passed At Danger.

rails due to for instance rain will also have lower adhesion than dry rails, rain will also tend to clean the tracks of other material (e.g. contaminants). Light humidity, however, combined with leaves in the autumn or other contaminants such as rust or industrial pollution, may create conditions of very low adhesion. Besides contamination and humidity, actual creation of low adhesion also depends on how previously passing trains have compressed and conditioned the third layer and is thus impossible to predict with certainty and precision (Jensen & Klit 2013). Tests carried out in the Netherlands showed how very low adhesion could arise at different locations and then disappear or move within short time (van Steenis 2010).

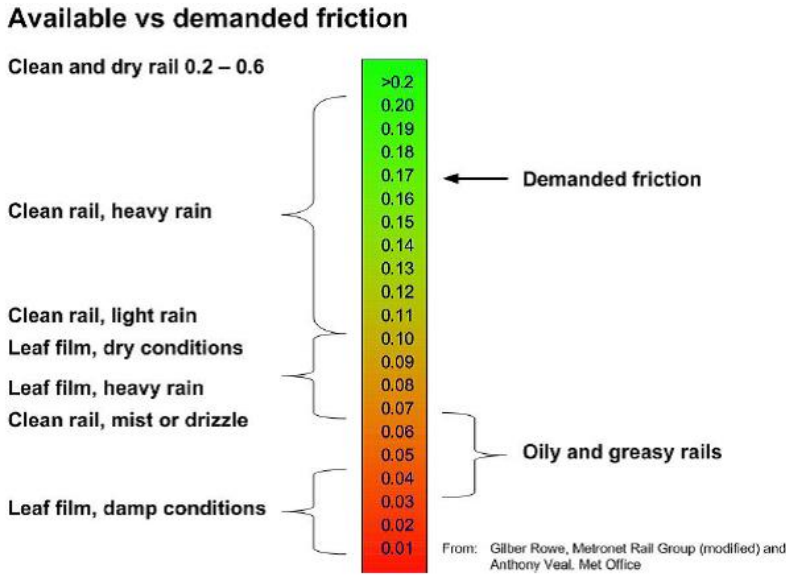

Figure 1 shows different levels of friction (adhesion) compared with the friction required for railway traffic, while describing the characteristics of typical corresponding adhesion layers (Nilsson 2013).

While other factors can reduce adhesion, e.g. oil and grease, the most common problem in Northern Europe and North America is associated with leaves on the line occurring in the autumn season (Spiess 2013).

As previously indicated, the phenomenon is based on a combination of multiple factors making accurate prediction impossible. There are, however, various means for identifying critical areas and times that allow for a useful estimation of enhanced risk based on a number of parameters, as indicated in section 2.1.

1.2 Problems due to low adhesion

Low adhesion creates problems with both spinning and sliding. In the first case, wheels spin on the rail, resulting in problems with traction, causing delays and problems with timetable and regularity, and even damage to tracks. In the second case, wheels slide, leading to problems with deceleration and braking. While spinning is thus a problem of regularity and well-known to drivers and their organisations, slipping leads to station overruns and a direct safety issue in the form of SPADs.

Furthermore, spinning and sliding cause uneven wear and tear on the wheels in the form of wheel flats, in which case rolling stock may be taken out for maintenance, in some cases causing delays and cancellations, thus further problems of regularity; while spinning may damage tracks which also incurs costs for repairs.

1.3 Relevance

While the problem of low adhesion is as old as railway operations, where the basic friction is generally much lower than the corresponding friction for road traffic, various European countries have recently experienced periods with more severe problems (RAIB 2007c;RAIB 2011;Rijnaard 2013b;Voges & Spiess 2006).

A number of trends in modern railway traffic are suspected of aggravating existing problems with low adhesion:

- Modern disc brakes on the axle do not clean the running band of the wheel, as opposed to the older tread brakes.
- Shorter trains have fewer driving bogies and thus more problems with braking (Rijnaard 2013b;RSSB 2004a),
- Modern train sets are lighter and have more problems than older and heavier ones[2] (Rijnaard 2013b).

In addition to existing problems, the European migration to the new ERTMS signaling system is expected to increase the capacity of the railway by shortening the distance between running trains, rendering braking problems due to low adhesion more critical – although also providing additional opportunities for mitigation.

In summary, there are various reasons for improving management of low adhesion. On the one hand, it is a means to improve regularity in the autumn season, both directly by reducing delays due to traction (spinning) problems or sometimes station overruns, and indirectly by minimizing unavailability of rolling stock due to time for repairing wheel flats. On the other hand, it is essential to improve safety by reducing problems with braking and SPADS, although actual investments should be balanced to match the associated risks.

[2] The effect of train weight must be treated with caution, however. The argument was presented at a workshop in Copenhagen 2013, and subsequently specified by Arjan Rijnaard as the vehicle "getting insulated from the railhead due to not penetrating the leaf contamination layer" (Rijnaard 2013a). Yet the physical explanation is ambiguous. Older locomotive-powered rolling stock is heavier than modern trains and not prone to low adhesion (Voges & Spiess 2006), but this may be due to other factors than weight.

2 Different aspects of management of low adhesion

This chapter covers four main aspects of low adhesion management. The first section (2.1) focuses on various approaches to detection, monitoring and even forecasting of low adhesion: information that can be used for various other approaches. The next section (2.2) focuses on *preventive measures* to improve adhesion by track maintenance, generally carried out by infrastructure managers, though sometimes in cooperation with operators. The third section (2.3) focuses on various technical solutions to improve the train's reaction to conditions of low adhesion on the rail, in some cases with implications for human factors and organization – implications beyond the mere technical solution. The final section (2.4) focuses mainly on approaches to support the train driver's ability to cope with low adhesion, as well as a few other operator initiatives.

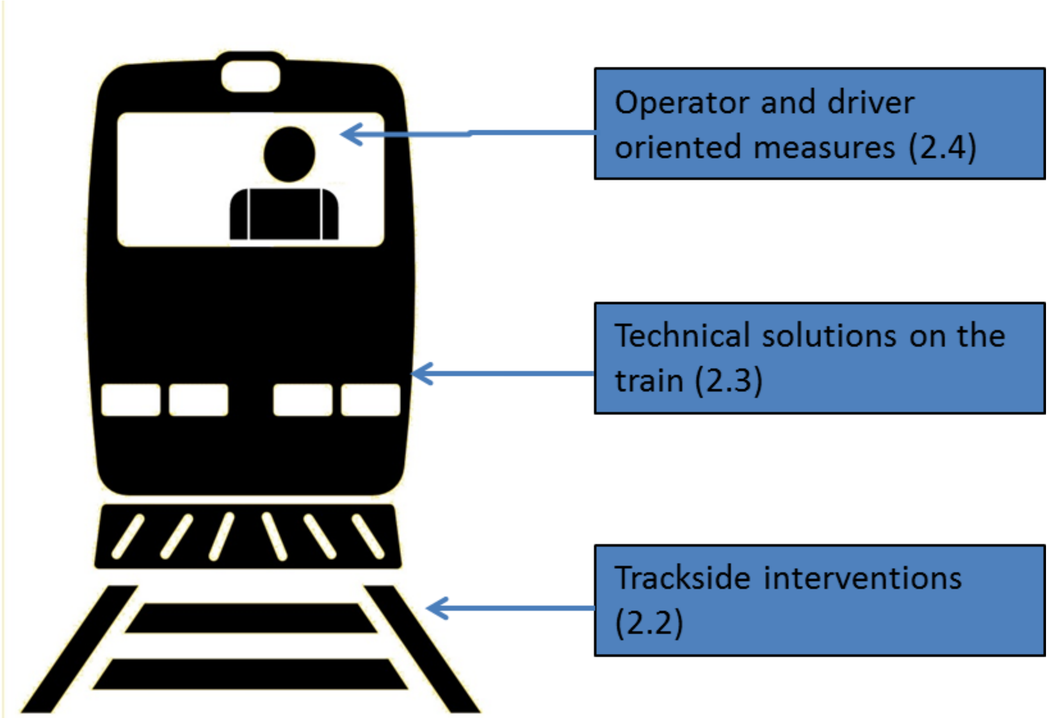

Figure 2 illustrates the orientation of measures described in sections 2.2-4.

2.1 Detection, monitoring, forecast

Before describing various methods employed it is useful to emphasize a distinction between ad hoc detection, more systematic monitoring, and forecasting. Monitoring differs from ad hoc detection by emphasizing a continuous or recurring observation of an area, preferably with the ability to determine both the start and termination of a period of low adhesion for a given area. This may be crucial to prioritize resources towards areas with an actual need, and to limit warnings and cautious driving. Forecasting emphasizes methods for identifying critical areas before they occur, with the option for early interventions and warnings.

Information about low adhesion conditions can be used for various purposes, which will also be described in more detail in later sections. The information can be used for maintenance purposes, typically by an infrastructure manager, to guide interventions towards critical areas, although real-time observations must always be balanced against long-term priorities. For instance, in the Netherlands the infrastructure manager will continuously monitor low adhesion across the country, but will not publish that information, since it might generate a public demand for immediate interventions, in contrast with planned activities based on long-term priorities.

Information about low adhesion can also be used to warn train drivers to take extra care and inform operators to consider possible countermeasures, again with due consideration to avoiding relieving drivers of responsibility for general awareness, and avoiding over-cautious behavior.

Information about adhesion conditions may also be used for adjustments to various technical systems. For instance, older Wheel Spin Protection (WSP) systems take account of low adhesion, but adapt badly to very low adhesion, while newer WSPs may be temporarily adjusted to such conditions – and thus require information about adhesion. Furthermore, Automatic Train Protection systems – e.g. ATC in Denmark – may be adjusted to incorporate more defensive braking curves in critical periods.

In any case, detection and monitoring of adhesion can also be used to simply estimate the criticality of the issue and support decisions about the potential benefit of intervening. Observations could thus also guide decisions not to invest more resources in low adhesion management, if deemed unnecessary.

This chapter will focus on detection techniques for operational purposes and not on methods employed for pure research. With this emphasis in mind, practical implementation of observation should also be designed to observe the dilemma of 'information overload', the risk of gathering more information than can be processed. This dilemma is illustrated by the choice by infrastructure management in The Netherlands not to publish information about low adhesion, which might create a public demand to act on the information.

2.1.1 Methods of detection

Detection methods are generally based on information from trains operated by one operator driving on tracks that are normally managed by another organization, i.e., the infrastructure manager. Operators use tracks continuously with ample opportunity to experience and observe problems (including low adhesion), whereas the infrastructure manager has limited capacity to survey the lines, and limited access to tracks subject to intensive traffic.

In any case, detection and management of low adhesion are challenged by the fact that such conditions are temporary and thus require frequent monitoring, e.g. to cancel warnings.

2.1.1.1 Reports from drivers

The simplest method of detection is based on drivers reporting when experiencing low adhesion (RSSB 2004b). Such reporting can be either voluntary or mandatory. There are structures for reporting about low adhesion related to incidents that require explanation, both *safety* incidents such as SPADS, but also for regularity issues (delays, station overruns). Drivers may be required to offer explanations for delays, mostly used in negotiations between operator and infrastructure manager, and to provide information for passengers.

In addition to structures for reporting about specific incidents, drivers may also be encouraged to make voluntary reports about very low adhesion, e.g. minor acceleration or braking problems without critical consequences (FTPE 2012). For instance, warning systems in The Netherlands since 2003 (RSSB 2004b) and more recently in Denmark (Banedanmark 2013) have been based partly on driver reports.

Experience indicates that reports from drivers may be biased towards very low adhesion ('negative reporting'), with fewer incentives or opportunities to report about normal adhesion and thus about termination of a period with low adhesion. Reporting about low adhesion may be prompted by actual problems experienced by the driver, while there are no similar occasions for reporting about (return to) normal conditions. Furthermore, the uncertainties of, and incentives for, reporting about 'normal conditions' are ambiguous: normal conditions do not require attention, the *lack* of experience of low adhesion (e.g. no activation of WSP) is a poor guarantee of normal adhesion and the termination of a previously reported critical condition.

In this sense, reporting from drivers is more suited for detection than monitoring, although it may be possible to compensate for the biased reporting by implementing some time limit for reports about critical sites. This was implied in the Low Adhesion Warning System introduced in The Netherlands in 2003, where warnings were sent to driver passing through a critical area within the next two hours (RSSB 2004b).

2.1.1.2 Automatic detection (WSP etc.)

There are various opportunities to estimate adhesion based on data already collected on the train, such as the On-Train Monitoring Recorder (OTMR) or the Wheel Slide Protection (WSP) system. OTMR is similar to the so-called 'black box' recording events in airplanes and has extensive data, but these often have to be downloaded after an event and require interpretation. Modern trains are equipped with WSP systems that register and respond to slide and spin. WSP is controlled by a computer that can gather information about the frequency of these events with a useful indication of adhesion problems. This information, however, is not in itself related to the actual *location* of the train and therefore requires combination with location data, e.g. GPS on train, to identify critical areas with low adhesion.

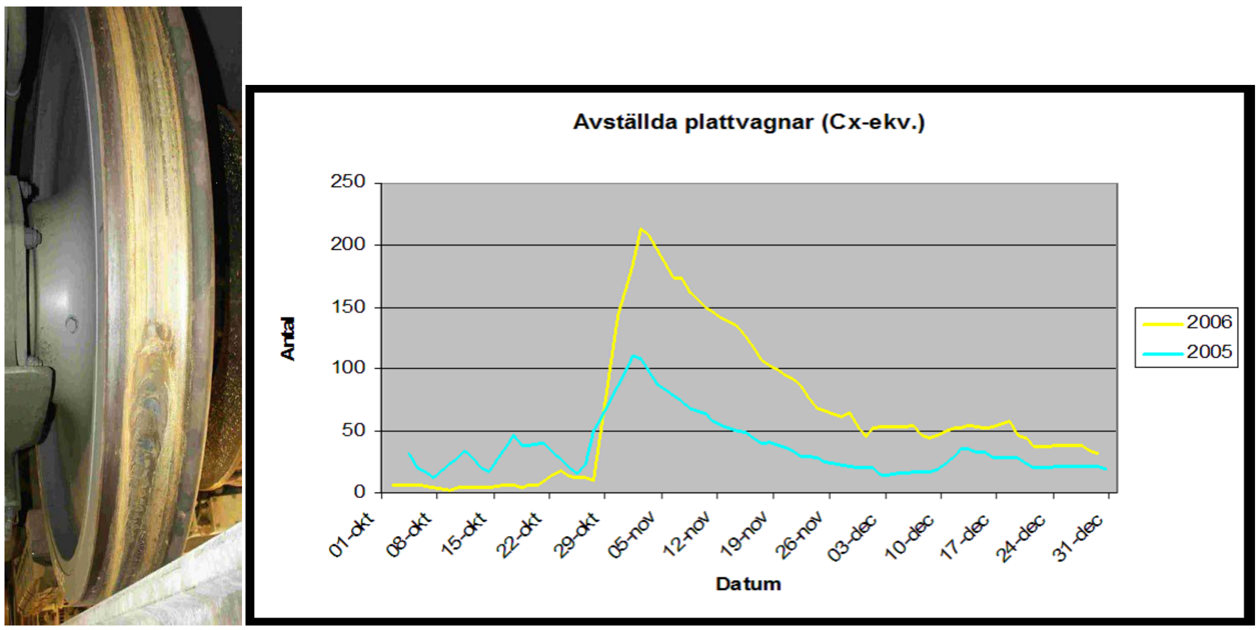

Figure 3. Stockholm Metro uses the number of wheel flats (example left) as a key indicator of autumn performance (right) (Stark 2013).

Automatically collected information via the WSP system, requiring no effort of human drivers, has the potential for providing recurring information about low and higher adhesion (high and low frequencies of slip and spin) and thus for monitoring the conditions of the line, rather than simply *detecting* ad hoc problems. Nevertheless, this method will also offer incomplete results: WSP is only activated during braking, and lack of WSP activation is not a guarantee against low adhesion. A brake action has to occur and the brake force needs to exceed the rail/wheel friction in order for this type of information being available.

However, all methods described so far detect low adhesion during braking (or accelerating) and thus report low adhesion *after the fact*. One challenge is that they only detect adhesion where braking has actually occurred. Another is that detection after the fact is too late to prevent the first incident, in the worst case a SPAD due to sliding. Once a driver experiences sliding, it will often be too late to react, and the situation is ‘out of his hands’ (e.g. left to the WSP system). While information from WSP is based on numerous non-critical events and thus has the potential to identify critical areas before a dangerous situation actually arises, it would be preferable to get the information earlier, preferably independent of actual braking.

Alternative methods are thus being considered for automatic measuring of low adhesion. One method uses optical sensors to register light reflected from the surface, depending on both topography and material, thus identifying several surface layers (Casselgren et al. 2013;Nilsson 2013). Another method is based on interpretation of general bogie movements, not restricted to braking, and was recently deemed promising by the RSSB (RSSB 2012).

Other methods give general indication of adhesion problems, though again with limited information about actual location. For instance, spinning and sliding cause wear and tear on wheels resulting in wheel flats, and observation of wheel roundness can thus provide information about increasing problems with adhesion (Casselgren et al 2013;Rijnaard 2013b) (see Figure 3).

2.1.1.3 Weather forecast

Besides reporting, registration and observation of low adhesion, there are also some means of prediction, since very low adhesion is often associated with specific weather conditions, and meteorological services already have well-developed methods for weather forecasting.

The problem with leaves on the line is associated with a limited time period in autumn, but it can be difficult to specify more precisely exactly when leaves start to fall. Leaf fall can often be provoked by a strong wind, which can be identified by a weather forecast. On the other hand, a continuous strong wind will also tend to spread the leaves and may thus reduce the problem with low adhesion.

Humidity is another meteorological cue for low adhesion, which is associated with some moisture, but also reduced by higher humidity, e.g. third layer washed away by rain. Problems may thus be associated with the dew point where air humidity condenses into water (Bridges & Jackson 2013). Here, too, some combination seems to be highly critical: a period of dry weather followed by slightly humid

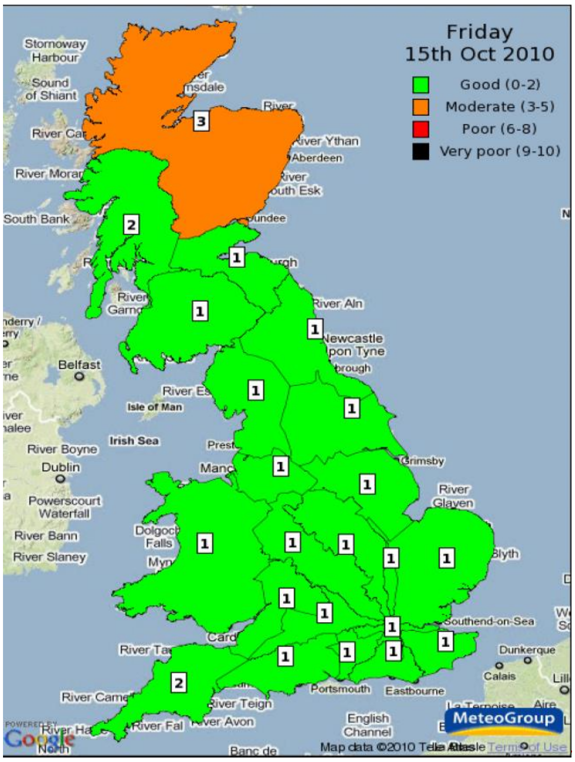

Figure 4. Weather services can provide predictions of adhesion levels, based on weather forecasts and other information. These predictions can be used as warnings for drivers (RAIB 2011) and modification of ATC braking curves (Nilsson 2013). Illustration from (Davidsson 2013).

conditions.

Rail companies, mostly infrastructure managers, in Europe cooperate with meteorological services to establish warning – preferably local – about low adhesion. Such information has the advantage of being preventive, but is also associated with some uncertainty, which poses a challenge to any type of response, e.g. warnings for drivers (2.4.6) or modification of ATC (2.4.7). Many possible responses or interventions are costly, whether based on resources directly invested, or in terms of delays or even reduced services.

2.2 Trackside interventions

Interventions against low adhesion problem may also be made by rail track organisation, typically by the infrastructure manager. Three different methods to improve adhesion are considered here: cleaning of tracks and removing of third layer, long-term management of rail-side vegetation and application of some layer (e.g. sandite[3]) to increase adhesion.

Such procedures are mainly performed by the infrastructure manager who, as mentioned above, has limited possibility of access to the tracks during day traffic, especially on sections (and periods) subject to intensive traffic. Operations such as water jetting and application of sandite are often performed by specialized trains that can only operate effectively at limited speed – at the cost of valuable capacity on the line. Network Rail in the UK has tried solutions with specialized sandite trains running at higher speed (RAIB 2011), whereas Deutsche Bahn in Germany has avoided this solution (Voges & Spiess 2006), and the Netherlands seems to have success in implementing some service (sandite application) on regular commuter trains (Rijnaard 2013b).

2.2.1 Water jetting, removal of third layer

The simplest form of intervention is directed at reducing an already existing problem by removing a third layer, e.g. leaves, and thus cleaning of railhead. This operation is performed by scrubbers and water jets on a low-speed service train, and a main challenge lies in timing the intervention: how to react swiftly to a problem once identified/reported, and with minimal disturbance to traffic. This operation is non-preventive and cannot be planned.

One downside to this operation is that water jets will add humidity to the tracks, sometimes causing problems for the first train after the service, as illustrated in an accident at Berlin (EBA 2008).

There have been experiments with other methods for cleaning the rails and removing the third layer, e.g. use of scrubbers, laser and microwave-generated steam cleaning. However, none were found feasible: scrubbers wear out quickly, and lasers only work at very low speed. While laser and steam were found initially promising, actual implementation would require heavy investments and was deemed unnecessary in comparison with existing methods (RAIB 2007c;RSSB 2002a;RSSB 2008;RSSB 2009).

[3] Sandite is an adhesion modifier consisting of sand, aluminium and a unique type of adhesive, used in the UK, Ireland and the Netherlands. For ease of reading, the term ‘sandite’ is used in this report as a general name for adhesion modifiers, possibly including similar products.

2.2.2 Long-term management of rail-side vegetation

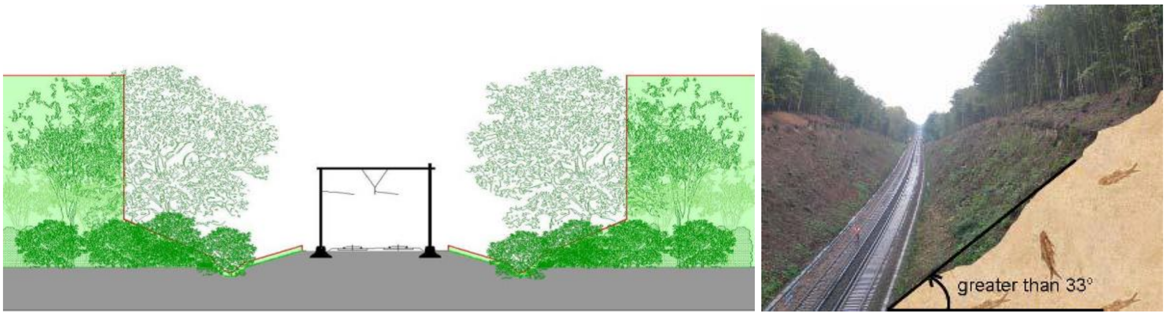

Figure 5. Vegetation management includes cutting of tall vegetation close to the rails and allows only the green areas (left), while full removal of vegetation may destabilize steep slopes (right). Illustration from (Rijnaard 2013b) and (Bridges & Jackson 2013).

More preventive interventions are directed towards the vegetation causing the problem. A drastic method is reduction or direct removal of rail-side vegetation. Full removal bears the risk of destabilizing the ground, especially on slopes on the rail-side (Bridges & Jackson 2013), but more cautious strategies are oriented towards simply limiting tall vegetation closest to the rails (Rijnaard 2013b) – although the very cutting process may temporarily contribute to contamination of rails (FTPE 2012).

Tracks can also be protected from leaves by fences along the line. In the Netherlands, such fences are colored brightly orange and thus also function as a reminder for the driver about local risk of low adhesion (see 2.4.6.1).

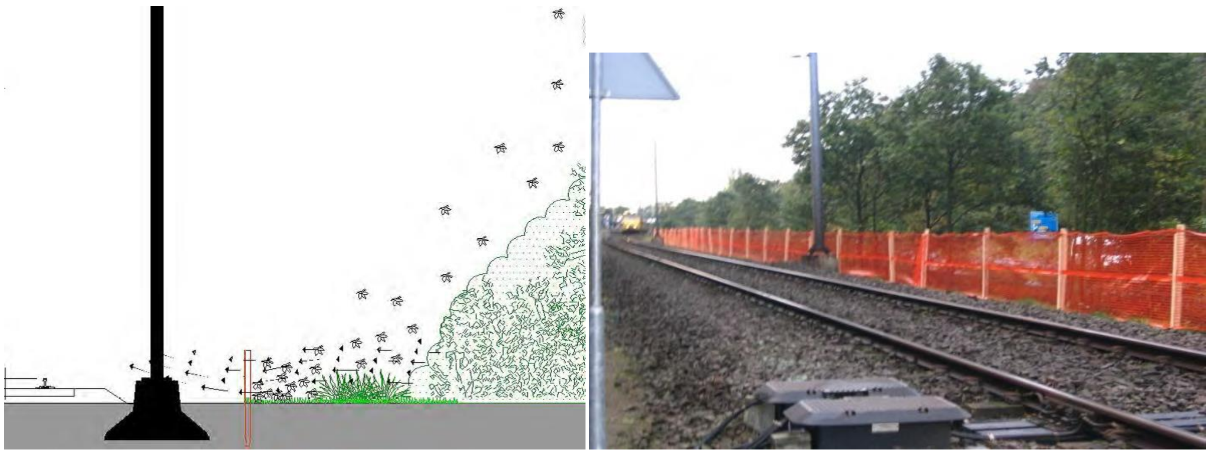

Figure 6. Leaf fences, some with bright colour to warn about adhesion risk. Illustrations from (Rijnaard 2013b).

2.2.3 Friction modification by application of sandite

A different and additional approach is to improve adhesion by applying a layer with high adhesion, mostly some component (e.g. sandite) based on sand and a gel to attach the material to the rail surface.

Sandite etc. can be applied either by hand, by trackside equipment, e.g. before and after platforms (for braking and accelerating) (Rijnaard 2013b), or by a vehicle running on the tracks.

Application by vehicle is hampered by the fact that specialized sanding trains will normally have to operate at a low speed to work efficiently. This may inhibit normal traffic, especially since it must be done frequently in critical periods. The need for frequent application is illustrated by the Stonegate incident in the UK, which occurred one day after the application of sandite (RAIB 2011), and by the decision in the Netherlands to apply it 2-4 times a day in critical periods (Rijnaard 2013b). Application by vehicle was thus rejected by Deutsche Bahn in 2004, because it would interfere with the time schedule (Voges & Spiess 2006). In 2009 Network Rail in the UK started experimenting with a similar product, which could be applied at higher speed, but a serious incident raised doubt about the quality of application at this speed (RAIB 2011).

Nevertheless, operators in the Netherlands now use special installments on commuter trains to apply sandite, either by a separate car or, since 2010, by applications equipped underneath commuter trains (Rijnaard 2013b) (see Figure 7). In this way, sandite can be applied at higher frequency without disturbing the time schedule, and the application is speed regulated to avoid problems with imprecise application (see above). This procedure requires close cooperation between the infrastructure manager responsible for track maintenance and the operator operating the train.

Figure 7. Application of sandite: trackside, by specialized vehicle or from installment on commuter train (in the Netherlands). Illustrations from Internet and (Rijnaard 2013b).

There are other challenges associated with the use of sandite (and sanders on the train, see later). Sand and sandite create a nonconductive layer on the rail and may thus interfere with existing systems to register the location of train, essential to the signaling system and thus to safety (Emery 2011;RAIB 2007c). Sand may also interfere with operation of switches (Spiess 2013).

2.2.4 Other measures by infrastructure management

In addition to these types of track maintenance, other measures can be taken by infrastructure management – measures that are oriented towards operation.

Infrastructure management can thus impose speed restriction for critical areas to minimize the risk of excessive braking distances and SPADs. By itself, however, such a measure may aggravate problems for a driver trying to keep the schedule (Scholdan 2013), and for the operator.

Figure 8. This sign warns Dutch car drivers about preventive closing of a level crossing behind a platform for early morning trains (Rijnaard 2013b).

Another measure is taken by the infrastructure manager in the Netherlands: preventive closing of level crossings behind a platform for early morning trains (Rijnaard 2013b), to protect car traffic from trains overrunning the station (see Figure 8). This measure has the additional effect of signaling caution and awareness of low adhesion issues to the public.

2.3 Technical solutions on the train

In contrast to the track-side measures described in 2.2, we now review a number of train-side interventions that are available to guiding or improving train performance. This section focuses on purely technical solutions on the train available to the operator, while also emphasizing possible human and organizational implications for driver and operator. These solutions are thus often not simple technical solutions that improve braking (or accelerating) independently of human or organizational factors, but will typically require some management and operational activities.

2.3.1 Sanders

With this solution, almost as old as the railways, the train is equipped with containers of sand that can be applied – by the driver or automatically – to improve adhesion, whether for braking or accelerating. Sanders are used and considered indispensable in many European countries, including the UK and Germany, but avoided by others due to a number of challenges.

There are challenges with maintenance and application of sand. The amount of sand in the containers must be sufficient to be available for critical situations, and two critical SPADS in the UK suffered from lack of sand (RAIB 2007b;RAIB 2011). It is therefore essential to have proper procedures for maintenance and refilling of sand containers, and this requirement has been considered unfeasible in the Netherlands where trains are not kept in depot overnight due to intensive use (Rijnaard 2013b).

A related challenge is the proper – timely and adequate – application of sand, which can either be deliberate (by the driver) or automatic, typically linked to a specific braking level. The criticality of timing is illustrated by a SPAD incident at Esher in the UK (RAIB 2007a), which was worsened by the late – automatic – dispensing of sand. But dispensing of sand can also be too early and too 'generous', which will require frequent refilling and may also lead to problems with excessive amounts of sand on the line (see below).

The efficiency of sanding will also depend on the speed of the train. Old systems operate independently of train speed and thus vary much with speed, dispensing relatively large amounts (piles of sand) at low or no speed while spreading the same amount imprecisely on larger areas at high speed – in which case the sand is simply blown away, with no effect on adhesion. These problems have led to doubts about the efficiency of sanding for high speed trains, but have been improved in newer systems where dispensing is speed regulated (Rijnaard 2013b;Spiess 2013) and controlled by high pressure jets.

Besides problems with the efficiency of sanding, sand may also create problems for the railway, as already mentioned in relation to sandite. Sand may interfere with existing systems for registration of trains and the track occupancy so critical to the signaling system (Emery 2011;RSSB 2002b). And excessive amounts of sand may disturb the operation of points – a problem that may be reduced by a more accurate application of sand, avoiding areas close to vulnerable installations.

2.3.2 WSP

Modern trains are equipped with Wheel Slide Protection systems, a technology used in the railway for several decades and similar to the more recent ABS system for cars. The system automatically detects when wheels are sliding during braking and reacts by releasing and reapplying brakes to achieve better effect. This operation relies on a registration of actual train speed, preferably independent of wheels subject to low adhesion.

One challenge with WSP is thus the proper observation of train speed. If this observation is based on sliding wheels, the WSP will believe that the train is actually slowing and sees no need to release and reapply the brakes.

A number of incidents have revealed that first-generation WSP systems, while operating with acceptable efficiency at low adhesion, are less efficient at very low adhesion and have actually been "one of the causes for the unusual overshooting of breaking distances on rails subject to autumnal conditions" (Hase et al. 2005) .

As a solution to this problem, newer generations of WSPs have implemented different adhesion modes, allowing users to select a special mode with adjusted parameters for conditions of very low adhesion. This solution requires operators to install a new WSP or at least implement a software update (Rijnaard), but it also requires relatively detailed information about adhesion conditions in order to 'fine-tune' the WSP.

2.3.3 Magnetic track brakes (MTB)

Magnetic Track Brakes operate by direct contact with the rails, hence independently of rail/wheel contact. They still depend on contact with rails and are therefore affected by low adhesion due to a third layer, but will also have some effect of cleaning the rails of such contamination – although UK experience found such an effect to be very limited (RSSB 2002b). The magnetic brake is pressed on the rails by magnetic force, thus the friction force is independent of the weight of the train.

Figure 9. Magnetic Track Brake (in red).

MTBs can have a negative effects on track circuits and thus interfere with detection of track occupancy and signaling systems and have for this reason been avoided in the UK (RSSB 2002b), while they are regarded as indispensable safety measure in other countries (Rijnaard 2013b;Spiess 2013;Voges & Spiess 2006).

MTBs are heavy compared to newer and lighter train sets and are generally only used occasionally for emergency braking to minimize wear due to contact with rails and generation of heat (Emery 2011;RSSB 2002b). Drivers may be tempted to use the MTBs more frequently, at the risk of reducing their efficiency in emergency situations (RSSB 2002b).

2.3.4 Eddy Current brakes

These brakes use magnetic fields that induce electrical eddy currents in the rail head that in turn produce a resisting force on the moving magnets. The brake's magnets are not in contact with the rail head, there is a small air gap of a few millimeters. Eddy current brakes thus have the advantage over the MTBs of being independent of existing adhesion.

However, they are also heavy, tend to generate heat, are less efficient at low speed and suspected of interfering with track circuits (Emery 2011;RSSB 2002b).

2.4 Operator and driver-oriented approaches

Various measures are taken by train operators to cope with low adhesion, besides the technical equipment of trains. Several measures are oriented towards supporting and guiding the train drivers in their attempt to cope with low adhesion conditions, while a few measures are independent of train drivers. The latter are presented first.

2.4.1 General operator initiatives

Since some types of rolling stock (lighter and shorter) are more sensitive to low adhesion, train operators can reduce problems by using more 'adhesion robust' train sets – longer and heavier – in critical periods. In UK, shorter train sets are thus combined to "reduce slip risk" during autumn (RSSB 2003).

Other operator measures focus on timely maintenance of train axles and wheels exposed to increased wear resulting in wheel flats (Nilsson 2013;Rijnaard 2013b).

2.4.2 Driving techniques

Operator initiatives oriented towards the driver must take their starting point in the driver's confrontation with low adhesion.

The basic technique in coping with low adhesion is so-called 'defensive driving': to brake earlier and lighter (see Figure 10). The driver starts braking earlier than under normal conditions, starting with limited brake power (a low brake level). The second element of this technique (light braking) has been slightly modified based on experience from SPAD incidents, the driver now having to start using a somewhat higher brake power. One reason for brak-

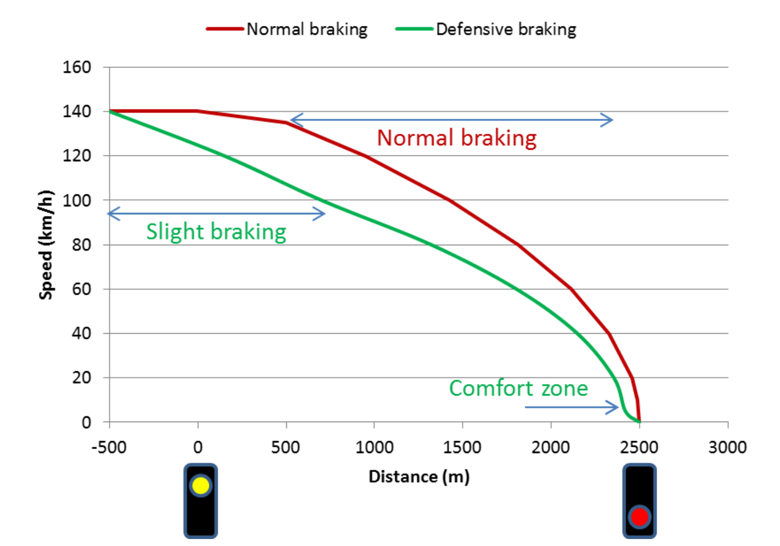

Figure 10. Defensive driving requires earlier braking (green), in contrast with a steeper braking curve characteristic of a non-defensive approach (red). Based on (Emery 2011).

ing harder from the beginning is to make better use of spots with higher adhesion when available (RAIB 2007c).

In addition to the regular brakes, the driver can also make use of additional systems such as sanding and MTB. Sand can be used deliberately by the driver or released automatically, in which case the driver still needs to be aware of the use. The driver can react to signs/cues of low adhesion and activate additional systems.

In the UK, sanding is linked automatically to the WSP, but not at the lowest brake level – in order to limit the use of sand, to avoid emptying of containers and limit unwanted consequences on the rails (wear and tear, track circuit problems). However, this limitation leads to ambiguous feedback to the driver, who must know *when* to release, or whether sand has been released automatically. There is only one lamp for WSP activity, which the driver normally also associates with sanding – which would be a misconception at the lowest brake level.

Some of these driving techniques are highly dependent on specific technical designs (brake levels, sanding, WSP indicators), but the general point to emphasize is that the driver needs feedback about low adhesion during braking (WSP indicators), and means for activating additional systems (e.g. MTB, sanding) when necessary, but not excessively – and/or to confirm the activation of such systems.

Besides the above emphasis on the drawbacks of the additional systems and the need to limit their use, the very technique of defensive driving also has the disadvantage of being slower than normal braking behavior and thus causing delays. This leads to problems with timetable and passengers and may even press other drivers to drive – and brake – more aggressively, with the increased likelihood of SPADs and station overruns. These problems lead to concerns of drivers being over-cautious (van Steenis 2010), one infrastructure manager even arguing that "*"defensive driving" by new drivers was aggravating the problem*" (Clark 2003), thus emphasizing the need to limit the use of defensive driving to situations where it is necessary, while avoiding it under normal conditions. This again emphasizes the drivers' need to have clear indication and cues about when to use defensive driving techniques.

While the drivers should thus avoid overcautious driving, they also depend on early cues and previous knowledge of critical sections to act as early as possible – since they will often be 'powerless' once on a section with very low adhesion.

Critical cues available to the driver are thus; knowledge of critical sections with a higher risk of low adhesion; critical weather conditions (low moisture, possibly following a longer dry period); driving the first train in the morning or on a line with little traffic or as the first train after the cleaning train (FTPE 2012).

Besides these cues, the driver's reaction will also be based on other information, some of which may be ambiguous.

One such example is the driver's expectation of braking effect. Drivers will thus base their braking approach on experience with the train's braking power. They will often have learned, during dry periods in the summer, to expect very high effect when increasing the brake power. However, this experience and expectation can be misleading during periods with low adhesion (Scholdan 2013;Spiess 2005).

Other examples of ambiguous information available to drivers are (depending on technology): WSP indicators and its connection to sanding (as already mentioned); a speedometer based on movement of wheels and thus vulnerable to low adhesion; information about available brake power (Spiess 2005).

2.4.3 Training of drivers

There are different ways for an operator to guide train drivers towards optimal behavior when facing low adhesion. One way is to provide training to teach drivers awareness about cues and the proper braking technique (see above). Train driving is a highly practical profession, and training will often emphasize practical experience. The typical education of train drivers includes a period of actual driving with an instructor, but it is difficult to ensure experience with low adhesion, especially outside the autumn season. Such experience can be provided by other means, e.g. in the form of "*computer-based awareness and instructional training*" (Voges & Spiess 2006), such as driving cab simulators (see Figure 11), or the use of separate sections with artificially modified low adhesion, so-called 'skid pan training' (AWG 2009;Mann 2013).

Figure 11. Driving cab simulator. Illustration from (AWG 2009).

In any case, practical training will have to be adapted to different types of trains.

2.4.4 Instructions, driving policies etc.

Defensive driving techniques can also be implemented by the operator as a *driving policy*, requiring the driver to drive – and brake – in a specific way, rather than relying on the driver's own professional expertise and judgment. Driving differently would then be judged as non-compliance, with possible repercussions for the driver.

The use of driving policies varies among the European countries, such a policy playing a crucial role in a number of adhesion incidents in the UK autumn 2005 and treated as an instrument for improvement and organizational learning, while largely avoided in Denmark.

It may be asked, why have a driving policy and not simply rely on the driver's professional judgment – as it is surely in the driver's own interest to avoid accidents? One advantage of a policy would be to guard against reckless driving, while another might be to protect the driver – and safety – in possible conflicts between safety and time schedule. The driver will always be encouraged to drive on time and to catch up with delays – and may be questioned about such delays, but a driving policy will defend the use of defensive driving.

There are also drawbacks, however. The technique canonized as driving policy may be fallible and not fit every conceivable situation, or they may not be updated with recent developments. For instance, it may be difficult to specify the meaning of 'braking light', when some trains have only three steps, other have several, and some trains use variable braking force. In some situations, a driving policy may prevent the driver from using skills to make a professional judgment leading to another and perhaps safer approach. In Denmark, the driver's trade union was against a specific 'autumn instruction', arguing that it draws attention away from low adhesion outside the autumn season (Østergaard 2012).

In the UK, there are no policies issued by the RSSB, but a guidance note (ATOC 2003) by the Association of Train Operating Companies (ATOC), which has been implemented as driving policy by several operators. As previously indicated, this policy instructed drivers to brake 'light and early' in case of low adhesion, where 'light' was generally interpreted as 'step 1'[4].

As already indicated, this driving policy was examined as one of the contributing factors for several incidents, since 'step 1' does not release sand and probably makes insufficient of possible sections with higher adhesion. The driving policy was thus modified by several operators after the autumn 2005 incidents (RAIB 2007c).

A more recent incident, however, illustrates that this policy – and technique – depends on the availability of sand – the release of sand being one of the reasons for going directly to brake step 2 (see previously). At Stonegate, the driver during the incident followed the policy using step 2, and proceeding to step 3 and then applying the emergency brake after experiencing insufficient deceleration. He later – after the incident – used the outdated procedure of braking lightly and early, with better effect, but then reverted to the official policy to avoid critique for non-compliance. Evidence showed that the train was out of sand, eliminating one advantage of brake step 2, and that the subsequent increase of brake power actually resulted in slower deceleration (RAIB 2011). The incident illustrates the – counter-intuitive – inefficiency of braking harder than the adhesion available, a challenge normally controlled by the WSP system. The driving policy depends on the availability of sand and should allow for a different approach, should sand be lacking. The operator has thus revised the driving policy, which no longer requires mandatory use of brake step two.

2.4.5 Autumn schedule etc.

Low adhesion during autumn increases the risk of delays, both due to defensive driving, speed restrictions and problems with acceleration. This leaves drivers with an increased pressure to catch up with delays, and thus to drive – and brake – more aggressively. The drivers are thus faced with an even greater conflict between the general requirement to keep the schedule and the passengers happy, and the need to drive safely.

Various measures can be taken to relieve the driver of this pressure and/or take account of the actual delays caused by autumn conditions. A mild measure is used in the Netherlands to gain more driving time between stations by having shorter stops at station platforms (Rijnaard 2013b). This solution seems to presuppose that normal seasons leave ample time for entering and exiting at station platforms and may require extra staff on platforms to assist e.g. elderly and disabled passengers.

Figure 12. Special timetable for autumn season. Example from (AWG 2009).

A stronger measure is to take account for delays by having a separate schedule for the autumn season (Emery 2011), e.g. in UK (Clark 2003). This solution represents numerous challenges to operators and infrastructure management. There will be fewer trains in autumn and overall reduced

[4] This policy is based on a braking system with three steps + emergency brake, where step 1 is analogous to a braking rate of 0.3 m/s^2, step 2 to 0.6 m/s^2 and step 3 to 0.9 m/s^2 (RAIB 2007c).

capacity for passengers, passenger confusion due to changes in schedule, and huge challenges with inter-connections between different lines and different operators.

Therefore, most countries struggle with alternative solutions to avoid a specific autumn schedule, as emphasized in both Germany and the Netherlands (Spiess 2006;van Steenis 2010).

2.4.6 Warnings

Drivers can be supported by warnings about low adhesion conditions, based on various types of information (see section 2.1).

2.4.6.1 Static, site-based warning

One type of warning informs the driver about specific areas with a known risk of low adhesion, based on rail-side conditions (e.g. vegetation) or history of incidents. This information supplements the driver's own knowledge of the line – knowledge generally required for train drivers. The driver must then use additional information, e.g. weather condition and previous weather, to estimate the current – time-based – risk of low adhesion and show proper precaution.

This information can be provided by signs along the track, or by colorful fences that serve both to protect the track from leaves, *and* to warn the drivers about the presence of such leaves. There are some ambiguous aspects of such signs, however. On the one hand, they seem to exempt the drivers from reporting further problems, which might otherwise inspire the infrastructure manager to introduce speed limits (Emery 2011). Some operators thus encourage their drivers to report serious conditions of very low adhesion for areas already marked as critical (FTPE 2012). On the other hand, the associated or implied sign of 'end of low adhesion' may create a false impression of 'good adhesion' and cause an untimely relief of driver vigilance, since adhesion does not always obey to signs (Emery 2011).

2.4.6.2 Time-specific warnings

Another type of warning informs the driver of specific 'local'/'current' areas with low adhesion based on updated information. One such example was previously used in the Netherlands, where a measurement or a driver report initiates a 2 hour period of 'low adhesion' for that particular area, during all drivers passing through the same area are warned by a text message (SMS) alert by the Region controller (RSSB 2004b).

2.4.6.3 Forecast based on weather

A third type of warning is predictive and based on weather forecast. One such example is used in the UK and illustrated in the investigation of the Stonegate incident. The infrastructure manager provides a forecast indexing the risk of low adhesion conditions on a scale from '1' ('Good') to '10' ('Bad'), where '9' or '10' "*indicates a 'black' day, corresponding to 'extreme leaf fall contamination' being expected*". The driver receives this information when booking on a station, by reading a notice (RAIB 2011).

The use of weather forecasts has the advantage of being predictive, but with considerable uncertainty. According to a recent Dutch study, "[t]he existing model for predicting low adhesion … is not good enough to warn drivers with a great level of reliability or to use the warning to take certain measures" (van Steenis 2010).

An older RSSB report emphasizes the need for warnings "to be appropriately localised so as not to impact unnecessarily on train performance" (RSSB 2004b), illustrating the need for a proper combination of site specificity (see section '2.4.6.1') and actuality.

2.4.7 ATC and similar

Parameters in Automatic Train Protection systems, e.g. ATC in Denmark, can be adjusted to implement flatter braking curves and longer braking distances. This will let the automatic system start braking earlier than otherwise, indirectly instructing drivers to brake earlier to stay within the allowed braking curve, thus encouraging automatically towards 'defensive driving'.

While the ATC system is a technology installed on the train, yet coupled to the signaling system, the adjustment of ATC parameters is an operation performed by the driver or by the operator. This adjustment is thus a human or organizational operation rather than a merely technical solution.

Adjustment of ATC braking curves depends on information about low adhesion and may be difficult to adapt to actual conditions that are difficult to predict and monitor, especially when 'low adhesion parameters' should only operate when necessary and thus be cancelled when the problem disappears. It may be easier to use these parameters for a longer, fixed period, typically in autumn – at the risk of not matching actual conditions of low adhesion or operating with lower efficiency (longer braking distances with less extensive use of railway capacity, e.g. fewer trains).

This approach, a combination of an estimation of adhesion and selection of braking curves in the ATC is implemented in a metro line within Stockholm Public Transport. A prediction of adhesion level (levels 1-3) is generated based on weather forecasts, traffic and work with possible contamination, and this prediction is then used, among other suggestions, to select among three different brake modes with different brake curves (Nilsson 2013).

3 Approaches in selected European countries

Various European countries have recently experienced periods with severe problems of low adhesion (RAIB 2007c;RAIB 2011;Rijnaard 2013b;Voges & Spiess 2006) and have arrived at different approaches to adhesion management, reflecting different national 'paradigms' with particular combinations of measures. Comparing Germany with the Netherlands, in particular, illustrates how some measures depend on specific conditions, while excluding other measures.

Germany reacted to an alarming number of problems during autumn 2003 by mitigative measures focused on improving the performance of rolling stock in conditions of low adhesion. The German solution is thus a combination of sanders, magnetic track brakes and an update of the WSP systems. Use of sandite or similar was considered, but deemed unfeasible due to the interference of the special sandite service trains with regular traffic.

In the Netherlands, however, a different combination was selected. While using MTB, sanding on the trains - as used in both Germany and the UK - was deemed unfeasible, since the rolling stock is used extensively and is not kept in depots during night, and thus with no opportunity of reliable refilling of sand. Instead, the solution focuses on preventive measures for improving adhesion by frequent application of sandite. The challenge from gaining adequate access for frequent application, 2-4 times a day in critical periods, is minimized by installing equipment on regular trains instead of using specialized vehicles that interfere with regular traffic. By this approach, track interventions - infrastructure management - are performed by regular trains run by an operator - and thus require close cooperation between operator and infrastructure manager.

This approach illustrates the cross-organisational challenge from low adhesion that concerns different railway organizations. This challenge is also illustrated by the fact that the Adhesion Working Group in the UK was created after the dissolution of British Rail in view of the need for coordination across rail/wheels organization. The AWG has carried out several research projects on different aspects of adhesion and also has members from other countries.

4 Summary

This report has presented a variety of measures to manage low adhesion problems, most already in use or at least subject to experiment in European countries. The measures described include methods for detection and monitoring, preventive measures for trackside intervention and mitigative measures in the form of technical solutions on the train and organizational measures oriented towards the driver.

- **Detection and monitoring**
  - Reports from drivers
  - Automatic detection (WSP or other)
  - Prediction based on weather forecast
- **Preventive trackside interventions (by infrastructure manager)**
  - Removal of third layer – by water jetting etc.
  - Long-term management of trackside vegetation
  - Improving adhesion by application of sandite or similar
- **Technical solutions on the train**
  - Sanders
  - Wheel Slide Protection (WSP)
  - Magnetic Track Brakes
  - Eddy current brakes
- **Operator and driver-oriented measures**
  - Training of drivers (with emphasis on practical experience)
  - Instructions, driving policies
  - Autumn schedule
  - Warnings for drivers
  - Modification of ATC (based on predictions)

As we have seen, the approaches used in other countries are to apply a combination of several measures. It would be convenient if the problem could be eliminated 'from the bottom up', but the phenomenon is too unpredictable for reliable preventive measures for timely removal of low adhesion layers by infrastructure management.

While there are several technical solutions to improve the performance of trains under low adhesion, none of these is adequate to achieve fully reliable performance (e.g. independent of driver vigilance). Furthermore, many technical solutions tend to require organisational management, e.g. for refilling of sanders and adjustment of WSP parameters depending on adhesion conditions - especially for very low adhesion.

Therefore, the performance under low and very low adhesion will still depend on driver vigilance and skills for reasonably cautious estimation of adhesion conditions and appropriate driving measures. These may again be supported by organisational measures for training appropriately for low adhesion, providing appropriate warnings and perhaps reducing pressure from timetable in critical periods.

Comparison among European countries also illustrates that there are constraints on various measures that cannot be combined freely. For instance, the use of sanders on trains depends on reliable processes and facilities for refilling, and sandite preparation requires a reliable method for timely application with minimal disturbance to normal traffic – possibly with coordination between train operators and infrastructure management.

5 Conclusion

Nearly all of the measures presented in this report will require coordination between the infrastructure manager and the railway operators, an interface which is now common to European countries. For instance, if the infrastructure manager runs a track cleaning train, leaving the tracks somewhat moist, the operator must know that the first regular train following this will have slightly degraded braking performance. Given the need for coordination, it is therefore likely to be more efficient to spell out a national strategy that defines, first of all, the risk control measures to be applied as well as their practical implementation and coordination, and that, as a second step, allocates responsibilities to individual stakeholders. This approach should be based on the recognition that the problems raised by low adhesion are challenges that are *shared* across organizational borders. Therefore, to focus on separate measures available to individual organisations may invite each of the parties to optimize within their own domain rather than collaborate on coordinating responses to shared challenges.

Selection and allocation of measures should be based on due consideration of both the risk associated with low adhesion and the cost and effect of measures. A recent report by the Danish infrastructure manager and the Danish Transport Authority (Trafikstyrelsen & Banedanmark 2012) has been able to identify only a few adhesion-related incidents, leading to an estimate that the risk is limited and existing measures adequate.

While existing evidence thus indicates that worries over low adhesion in Denmark should not be exaggerated, it may also be worth keeping in mind that the future calls for a more intensive use of railway capacity in Europe with shorter distance between trains and a more extensive use of highspeed trains, notably with the new signaling system, ERTMS. Furthermore, a better management of low adhesion not only serves as a defense against the risk of incidents, but may also serve to minimize losses from wear and tear as well as delays and associated public discontent.

6 Appendix: Table overview of measures

Type	Title	Chapter	Advantages	Challenges
Detection	Reporting	2.1.1.1	• Based on actual experience with low adhesion	• Biased towards 'negative reporting' of very low adhesion, not restoring of adequate adhesion
	Automatic detection	2.1.1.2	• Independent of driver alertness • Systematic monitoring	• Available data difficult to process
	Weather forecast	2.1.1.3	• Supports early warnings for drivers and infrastructure management	• Considerable uncertainty
Track maintenance	Water jets etc.	2.2.1	• Removes adhesion layers	• Lower adhesion for first train • Reactive: response to actual leaf fall etc.
	Vegetation management	2.2.2	• Preventive measure to minimize contamination	• Requires resources • Removal may create other problems
	Sandite etc.	2.2.3	• Preventive measure to improve adhesion	• Normally applied at low speed • Interference with regular traffic • Possible interference with track circuit • Possible interference with switches
Technology on trains	Sanding	2.3.1	• Instant improvement of adhesion	• Difficult at high speed • Possible interference with track circuit • Possible interference with switches • Requires reliable processes for refilling • Requires driver awareness of availability and activity
	WSP	2.3.2	• Indispensable	• Must be modified for very low adhesion
	Magnetic Track Brakes	2.3.3	• Clean the rail-head • Independent of wheel surface	• Heavy • Wear and tear • Only limited cleaning of railhead • Only for emergency • Only at high speed • Adhesion-dependent – contact with rails • May interfere with track circuit
	Eddy Current brakes	2.3.4	• Adhesion-independent	• Heavy • Only at high speed • May interfere with track circuit
Operator and driver-oriented	Driving policy etc.	2.4.4	• Clear instructions for inexperienced drivers • Instrument for organizational learning	• Difficult to adapt to specific equipment • May interfere with driver skill and vigilance
	Autumn schedule	2.4.5	• Relieves pressure on driver	• Reduces railway capacity
	Warnings for drivers	2.4.6	• Support driver alertness in critical periods and locations	• Difficult to time appropriately
	ATC	2.4.7	• Independent of driver vigilance and experience	• Difficult to time appropriately

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